NASA Quest Challenge
Charting a Course to the Moon

Part II ~ Spring 2009

Acknowledgments

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Overview

Purpose

Welcome to Part II of the NASA Quest "Exploration Through Navigation" Challenge! The purpose of this Challenge is to connect students in grades 5–8 to NASA's Lunar Crater Observation and Sensing Satellite (LCROSS) mission while teaching them about different methods of Earth-based and space-based navigation.

Learning Objectives

- Humans explore for reasons of necessity and curiosity, and exploration often leads to new innovations.
- Navigation skills are tools of exploration.
- There are different methods of navigation, and these methods vary whether you are at sea or in space.
- One method of navigation that is common to both voyages at sea and in space is celestial navigation (the use of planets, moons, and stars).
- Using multiple methods of navigation is better than relying on only one method.

Summary

The major concept, or big idea, behind this Challenge is **exploration**, with the content centering on **navigation** skills, tools, and methods. The essential question posed to students is, "**How will you stay on course?**"

In Part I* of this Challenge, students were tasked to chart a course from the Big Island of Hawai'i to Rapa Nui (Easter Island) using ocean navigation methods that were used in early Polynesian exploration. Outside of the classroom, students tracked the star Enif and determined if there is a relationship between the latitude of the observation site and the star's altitude at its upper culmination.

Now, in Part II of the Challenge, students will be tasked to chart a course from Kennedy Space Center at Cape Canaveral, Florida, to the Moon's north polar region using navigation skills appropriate for outer space. For this task, students will submit a navigation plan (as a class) to NASA Quest for experts to review. After constructing their navigation plan, students will be presented with a "problem situation" that they will need to solve using math and science skills. At the end of the Challenge, students will compare and contrast methods of navigating on Earth (at sea) and in space.

To keep students actively engaged and connected, weekly questions will be posed and winning answers will be awarded prizes. Additionally, opening and closing web casts will be hosted, allowing for direct interaction between students and subject matter experts.

Classroom Deliverables

Part I*: Hawai'i to Rapa Nui http://quest.nasa.gov/challenges/lcross2/	**Part II: Earth to Moon** http://quest.nasa.gov/challenges/lcross3/
• Map of ocean route	• Map of space route
• Navigation plan (format provided)	• Navigation plan (format provided)
• Image of navigation method or process	• Image of navigation method or process
• Star tracking data: latitude & altitude	• Compare/contrast Earth & Space nav

Structure

The structure of this Challenge is based on the Moenaha adaptation of the 4MAT method of learning used by the 'Imiloa Astronomy Center of Hawai'i. In this model, four driving questions are used to guide students through the learning process: Why? What? How? and If?

Ho'olohe: The Challenge begins by sparking the students' interest and bringing meaning to the task at hand with the question, "*Why* do humans explore?" Here the Challenge is made relevant to students' lives through images, stories, and discussion.

Ho'opili: Next, information is gathered and key concepts are taught to answer the question, "*What* methods can be used to navigate on Earth (Part I*) and in space (Part II)?" In Part II, special focus is given to the challenges of navigating an unmanned vessel in three-dimensional space.

Ho'ohana: After students explore select methods of navigation, they apply the skills they have learned by developing a strategy for "*How*" they will navigate an unmanned spacecraft from Earth to the Moon.

During this portion of the Challenge, classes submit their navigation plans to the NASA Quest Challenge team in the form of an image, explanatory text, and map of their route. Subject matter experts offer the classes feedback and pose questions for further research and consideration. Students, in turn, refine and submit their final navigation plans as to "how they will stay on course" and navigate to their destination. Midway through the Challenge, students will be presented with a problem situation in which they will apply math and physics to get a spacecraft back on course.

Ho'opuka: At the end of the Challenge, students expand the possibilities of their new-found knowledge by exploring the question, "*If* I can navigate, where will I go?"

***NOTE:** The "Exploration Through Navigation" Challenge is divided into two parts. Part I of the Challenge focuses on ocean navigation methods used on Earth, and Part II focuses on space navigation methods. This educator guide supports Part II of the Challenge. The two parts of the Challenge complement each other but ultimately stand alone. Participation in Part II does not require participation in Part I.

CHARTING A COURSE TO THE MOON

Concept or Big Idea: Exploration

Content and Skills: Navigation

Major Understandings:

- Navigation skills are tools of exploration.
- There are different methods of navigation.
- One common method on Earth and in space is celestial navigation.
- It is advantageous to utilize multiple navigation methods.

Essential Question:

How will YOU stay on course?

Driving Questions:

Why? (motivate)
Discuss exploration as a natural human endeavor that leads to human expansion and invention

What? (teach)
Learn about navigation skills, tools, and methods used in exploration

How? (apply)
Develop a navigation strategy and then verify and refine ideas

If?... (empower)
Consider places to explore with newly acquired navigation skills or create new ways to navigate

National Standards

Language Arts	
NL–ENG.K–12.4, Communication Skills	Use spoken, written, and visual language to communicate effectively with a variety of audiences
NL–ENG.K–12.8, Developing Research Skills	Use a variety of technological and information resources to gather and synthesize information and to communicate knowledge
Mathematics	
NM–NUM.3–5.3, 6–8.3, Compute Fluently and Make Reasonable Estimates	Develop and use strategies to estimate the results of number computations and to judge the reasonableness of such results; Select appropriate methods and tools for computing with whole numbers, depending on the situation, and apply the selected methods
NM–ALG.3–5.2, 6–8.2, Analyze Mathematical Situations	Represent the idea of a variable as an unknown quantity using a letter or symbol; Express mathematical relationships using equations; Use symbolic algebra to represent situations and to solve problems; Solve linear equations
NM–PROB.PK–12.1, 2, and 3, Problem Solving	Build new mathematical knowledge through problem solving; Solve problems that arise in mathematics and other contexts; Apply a variety of appropriate strategies to solve problems
Science	
NS.K–4.2, 5–8.2, 9–12.2, Physical Science	Position and motion of objects; Motions and forces; Transfer of energy
NS.K–4.4, 5–8.4, Earth and Space Science	Objects and changes in earth and sky; Earth in the solar system
NS.K–4.5, 5–8.5, 9–12.5, Science and Technology	Abilities of technological design; Understanding about science and technnology
NS.K–4.7, 5–8.7, 9–12.7, History of Nature and Science	Science as a human endeavor
Technology	
NT.K–12.3, Technology Productivity Tools	Use technology tools to enhance learning, increase productivity, and promote creativity
NT.K–12.4, Technology Communication Tools	Use telecommunications to collaborate and interact with peers and experts
NT.K–12.5, Technology Research Tools	Use technology to locate, evaluate, and collect information from a variety of sources

Vocabulary

attitude - the orientation of a spacecraft relative to the direction of travel

celestial - positioned in or pertaining to the sky or outer space

DSN - **D**eep **S**pace **N**etwork. An international network of antennas that supports interplanetary spacecraft missions and radio and radar astronomy observations

Doppler effect - an increase (or decrease) in the frequency of sound, light, or other waves as the source and observer move toward (or away from) each other. The effect causes the sudden change in pitch noticeable in a passing siren, as well as the redshift seen by astronomers.

escape velocity - the speed needed to break free from the gravitational field of an object, such as the Earth

free fall - the state of an object which is being acted upon solely by the force of gravity and not encountering air resistance, as in a spacecraft with its rockets off

gravity - the force that attracts (pulls) objects with mass toward one another

gyroscope - a device (spinning wheel or disk) whose axle is free to take any orientation and that is used for measuring or maintaining position, based on the principles of angular momentum. It is commonly used to maintain a reference direction in navigation systems.

innovation - a new method, idea, or product

LCROSS - (**L**unar **Cr**ater **O**bservation and **S**ensing **S**atellite) an unmanned, robotic NASA mission scheduled for Spring 2009 that will search for water ice at the Moon's polar region

LGALRO - **L**unar **G**ravity **A**ssist **L**unar **R**eturn **O**rbit to be used by LCROSS for navigation purposes

navigation - the art or science of directing the course of a vessel; method of determininig position, course, and distance traveled

propulsion - the act of driving or pushing forward; any method used to accelerate spacecraft and artificial satellites

rocket - a vehicle that obtains thrust by the reaction of the rocket engine to the ejection of fast moving fluid exhaust

sextant - an instrument with a graduated arc of 60º and a sighting mechanism used for measuring the angular distances between objects, especially for taking altitudes in navigation.

sidereal - of or with respect to the distant stars

trajectory - the path or orbit followed by a spacecraft

transfer orbit - elliptical path followed by a spacecraft moving from one orbit to another

voyage - a long journey involving travel by sea or in space

waypoint - a point between major points on a route

Ho'olohe (Why)

Driving Question:

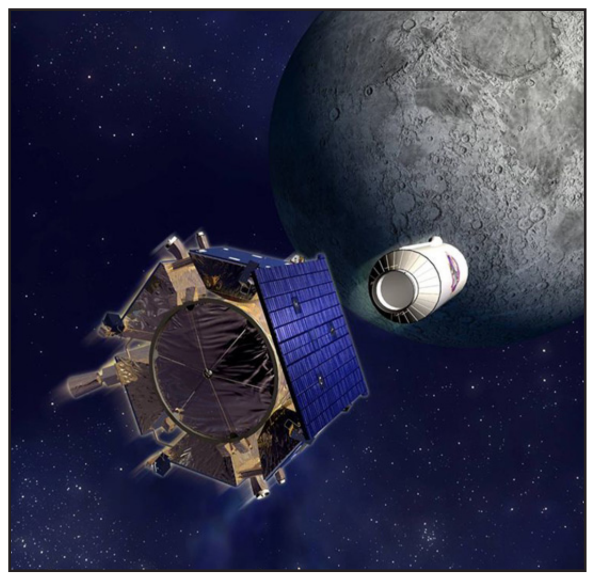
In January 2004, the United States announced a new policy for its future exploration of the solar system. This vision includes lunar robotic spacecraft missions slated for launch in 2009. The Lunar Crater Observation and Sensing Satellite (LCROSS) is one of these Lunar Precursor Robotic Program missions that will hopefully lead the way to future human exploration of the Moon and beyond.

To excite students about this Quest Challenge, show the following three videos:

NASA exploration video: http://www.nasa.gov/externalflash/Vision/index.html (50 second introductory video plus additional features to explore)

NASA LCROSS video: http://lcross.arc.nasa.gov (4 minutes, 20 seconds)

KQED Quest video: http://www.kqed.org/quest/television/view/26?gclid=CO2hxvnqpZgCFShRagodbD3oYw (10 minutes)



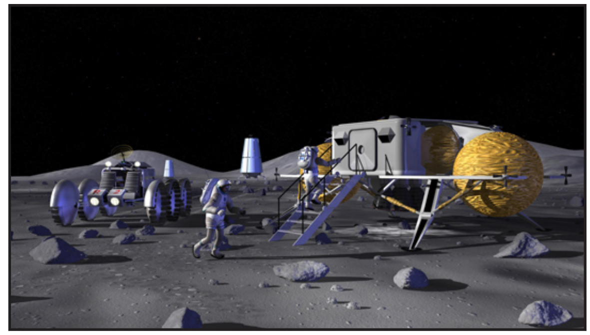
LCROSS representation

As stated in the LCROSS video, the primary objective of the LCROSS mission is to search for the presence of water, in the form of ice, in a permanently shadowed crater near one of the Moon's poles. LCROSS will launch from Earth on an Atlas V rocket and then position itself on a course toward one of the lunar poles. Upon approach, the Atlas V's Centaur upper-stage rocket will separate from the LCROSS shepherding spacecraft and continue on its course to the lunar surface. The Centaur will impact the Moon, creating a debris plume that will rise above the lunar surface. The LCROSS shepherding spacecraft, following four minutes behind, will fly through the debris and collect data with a suite of instruments including spectrometers, cameras, and a radiometer. After relaying the data back to Earth, the LCROSS shepherding spacecraft will impact the lunar surface, creating a second debris plume for scientists to analyze.

Transporting water and other goods from Earth to the lunar surface is expensive; therefore, finding natural resources, such as frozen water, on the Moon is important for future human exploration. If water exists, then it can be used in the process of establishing a lunar outpost, which would be a stepping stone to future exploration of the Moon as well as other bodies in our solar system.

Hold a class discussion around the driving question, “**Why do humans explore?**”   Responses may include:

Necessity – Since the earliest ages, humans have explored new territories for reasons such as growing populations, the search for food and natural resources, and the building and conquering of societies, etc. Part I of this Challenge focused on one example of early exploration, which was the migration of the Polynesian cultures thousands of years ago. (Read about Polynesian migration: http://pvs.kcc.hawaii.edu/L2migrations.html or http://www.pbs.org/wayfinders/polynesian.html)



Artist’s rendering of a Lunar Outpost

In the past 50 years, exploration has shifted from our home planet to the new frontier of space. As populations and climates change on Earth, humans are becoming more interested in establishing a lunar outpost, which would serve as a stepping stone for exploration of other regions in our solar system. Read about lunar outposts: http://www.nasa.gov/mission_pages/exploration/mmb/lunar_architecture.html

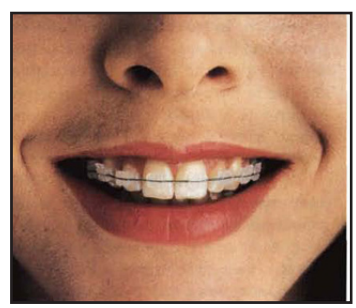
Moonrise over Lick Observatory
Mt. Hamilton, California

(Photo courtesy of Rick Baldridge)

Curiosity – Humans are natural explorers. People inherently like to know about the world around them. By 1500 BC, Polynesians were exploring the Pacific Ocean, and in the 15th and 16th centuries, many European explorers began traveling all over the world. By the 1950s and 1960s, human exploration expanded past our home planet and into outer space all the way to the Moon!

“Exploration is really the essence of the human spirit.”

Astronaut Frank Borman



Innovation – Exploration often leads to technological invention. Space exploration alone has resulted in many innovations. Shock-absorbing helmets, smoke detectors, and flat panel televisions are examples of “spinoff” technologies resulting from space exploration.

Read about NASA spinoff technologies at:
- http://www.thespaceplace.com/nasa/spinoffs.html
- http://www.sti.nasa.gov/tto/

NASA Spinoff Technologies: invisible braces, symmetrical golf ball, and aerodynamic bike helmet

~ The Search for Water Ice ~

The purpose of the LCROSS mission is to search for water ice on the Moon, but how could water ice be present on the lunar surface and where would it exist? The answer: comets and permanently shadowed polar craters. Comets are comprised of simple organic compounds, interplanetary dust, ammonia, frozen carbon dioxide, and... water. The bottoms of the craters located at the lunar poles are in permanent shadow, never receiving the Sun's light. The temperature in these permanently shadowed craters can be as low as -170º C (-275º F), allowing them to act as "cold traps." Water molecules, left over from comets that impacted the Moon's surface, may have migrated to these dark, cold craters over millions of years and could still be trapped beneath the surface. LCROSS is on a mission to find out!

Learn more about comets and the Moon's permanently shadowed craters by watching three videos produced by the Astronomical Society of the Pacific at: http://quest.nasa.gov/lunar/ASP/video.html

Cook up a Comet (4 minutes, 35 seconds)

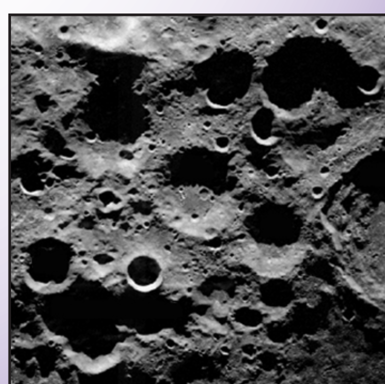
Finding the Right Crater (2 minutes, 10 seconds)

Making an Impact (6 minutes, 20 seconds)

Learn more about the possible existence of lunar water ice at:

- NASA LCROSS. About the Moon. http://lcross.arc.nasa.gov/AboutTheMoon.htm
- NASA Goddard Space Flight Center. Lunar and Planetary Science. The Moon: Ice on the Moon. http://nssdc.gsfc.nasa.gov/planetary/ice/ice_moon.html

If water ice exists on the Moon, then most likely it is beneath the lunar surface. The Atlas V's 2,000 kg (4,410 lb) Centaur upper stage will need to impact the lunar surface at high velocity and at a steep angle in order to eject enough lunar surface material for LCROSS to fly through and analyze. The Centaur is expected to impact the lunar surface at 9,000 km/hr (5,600 mph) and at an angle close to 70º, creating an ejecta plume over 10 km (6 miles) high! As part of this Challenge, students will need to plan their spacecraft's navigation route so that it, too, can achieve a steep-angle, high-velocity impact.



Learn more about craters and the LCROSS impact at:

- NASA LCROSS. Impact. http://lcross.arc.nasa.gov/impact.htm
- NASA LCROSS. Educatiton. http://lcross.arc.nasa.gov/education.htm
- NASA Quest. "Cratering the Moon" Spring 2008 Challenge. http://quest.nasa.gov/challenges/lcross/index.html

Ho'opili (What)

Driving Question:

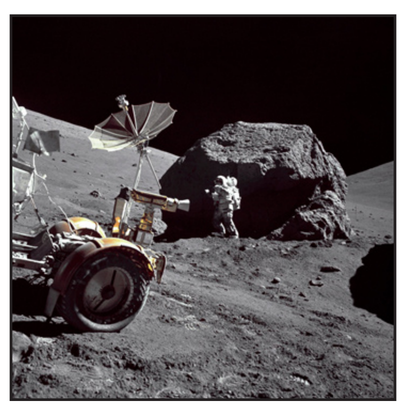
Human Space Exploration

Human exploration of outer space first extended beyond the telescope in the late 1950s with the Soviet Union's Sputnik program and the United States' Mercury project. On October 4, 1957, *Sputnik 1* became the first artificial satellite to orbit the Earth. Three and a half years later on April 12, 1961, Soviet cosmonaut Yuri Gagarin became the first human in space as he orbited Earth for 108 minutes in the *Vostok 1* spacecraft. On May 5, 1961, twenty-three days after cosmonaut Gagarin orbited Earth, United States astronaut Alan Shepard, aboard the *Freedom 7* Mercury capsule, became the first American in space. Then, on February 20, 1962, astronaut John Glenn aboard the Mercury spacecraft *Friendship 7* became the first American to orbit Earth. Significant space exploration achievements continued to occur over the next seven years leading up to the major milestone of landing a human on the Moon. On July 20, 1969, Neil Armstrong and Edwin "Buzz" Aldrin, astronauts of the Apollo 11 mission, became the first humans to step on the Moon. Although no human has returned to the Moon since astronauts Eugene Cernan and Harrison Schmitt of the Apollo 17 mission in December 1972, manned spaceflights in low Earth orbit have continued via Russia's Soyuz spacecraft program, the United States' Space Shuttle program, and more recently China's Shenzhou spacecraft program. Now, in 2009, the United States plans to return to the Moon via the unmanned, robotic **L**unar **Cr**ater **O**bservation and **S**ensing **S**atellite (LCROSS) mission. Depending on the mission results and findings, the LCROSS mission could be the first step to returning humans to the Moon!

> *"The important achievement of Apollo was demonstrating that humanity is not forever chained to this planet and our visions go rather further than that and our opportunities are unlimited."*
>
> Astronaut Neil Armstrong

Astronaut Buzz Aldrin
Apollo 11, July 20, 1969

Astronaut David Scott
Apollo 15, August 1, 1971



Astronaut Harrison Schmitt
Apollo 17, Dec. 13, 1972

Space

Double conjunction eclipse showing crescent Moon, Venus, and Jupiter

Navigation

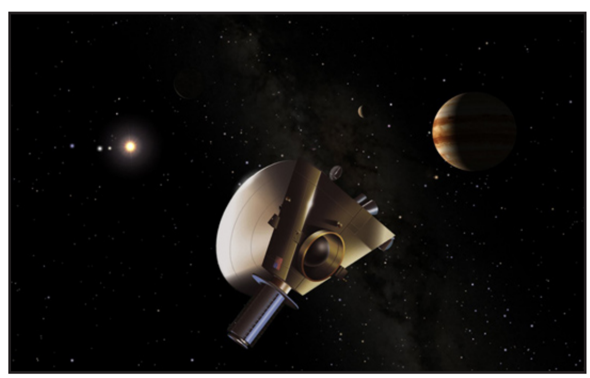
Navigation is the process of accurately determining one's position and planning and following a route to a destination. As was learned in Part I of this Challenge, ancient Polynesian wayfinders navigated thousands of miles across the Pacific Ocean without the use of modern instrumentation. Instead, they traveled the vast ocean using celestial navigation and their knowledge of the ocean waters, winds, and sealife. However, these methods of navigation are insufficient when it comes to navigating in outer space.

> *"And I think that still is true of this business – which is basically research and development – that you probably spend more time in planning and training and designing for things to go wrong, and how you cope with them, than you do for things to go right."*
>
> Astronaut Alan Shepard

The Cosmic Ocean

You can think of space as an endless, cosmic ocean. However, in space you must always think in three dimensions, rather than the two-dimensional reference frame you use for navigating at sea.

Because there is no air in space, the most important force acting on a spacecraft is not the movement of air (wind), but gravity. On Earth, winds can be unpredictable, but the effects of gravity on a body in space can be precisely calculated. One rule is that the closer you get to a specific star, planet, moon, or other celestial body, the stronger its gravitational pull. Likewise, the farther away you venture from that body, the weaker its pull.



Artist's conception of a Jupiter fly-by by the New Horizons spacecraft

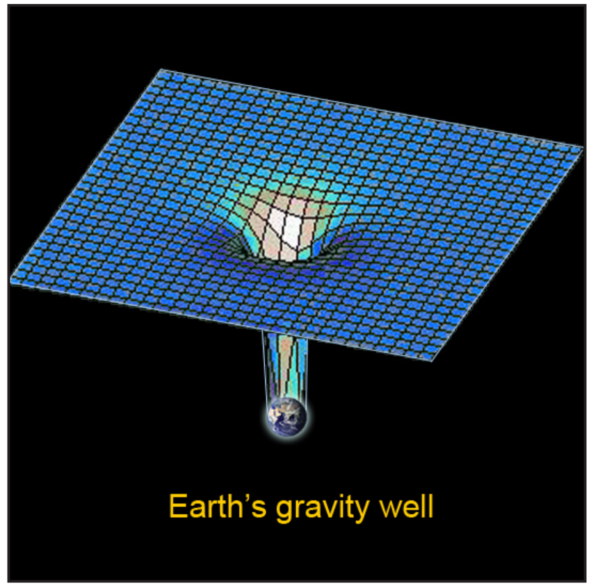
Another force that can change the motion of a spacecraft is a burst from its own rocket engines. A spacecraft that is not firing its engines is in a state of free-fall. That is true whether it is heading toward or away from Earth or another celestial body.

The Gravity "Well"

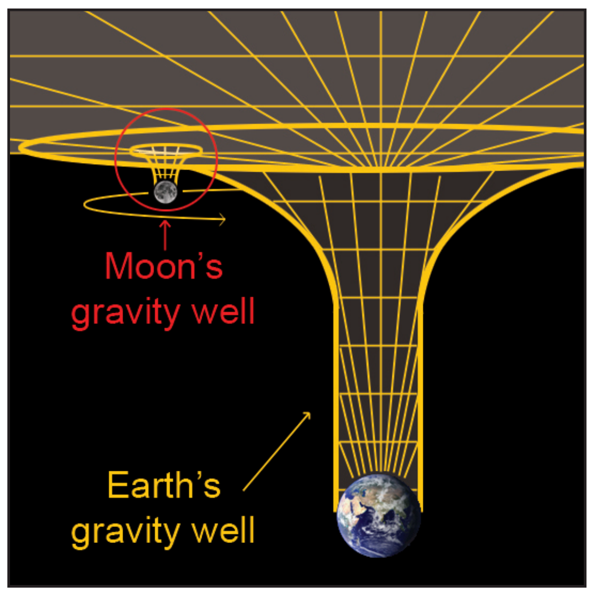
With all that in mind, imagine that a spacecraft traveling from Earth to the Moon is coasting up the side of a huge, invisible funnel with curved sides. Let's call it the Earth's "gravity well." Near the Earth, the sides of the well are steepest (that is, the pull of gravity is strongest), and it takes more force to "climb" out. As the spacecraft gets farther from Earth, the sides of the well gradually flatten out, and less force is required to move away from it.

Because it is just one-quarter the size of Earth and has only 1/8 the mass of Earth, the Moon's gravity "well" is much smaller than Earth's. Think of it as a small dimple indented into the outer slope of Earth's well.

Of course, the Moon does not stand still; it circles the Earth once every 27.3 days, moving at an average speed of about 2,200 miles per hour. (Since the diameter of the Moon is about 2,100 miles, that means that on average the Moon travels slightly more than its own diameter every hour.) The fact that you are trying to hit a moving target makes flying from Earth to the Moon more difficult.



Sample illustrations of gravity wells



XPRIZE Foundation has posted a two-minute animation on YouTube titled "Earth and Moon Gravity Well Comparison" that helps illustrates this concept. (1 minute, 52 seconds)

http://www.youtube.com/watch?v=VBQHtF3WhMw

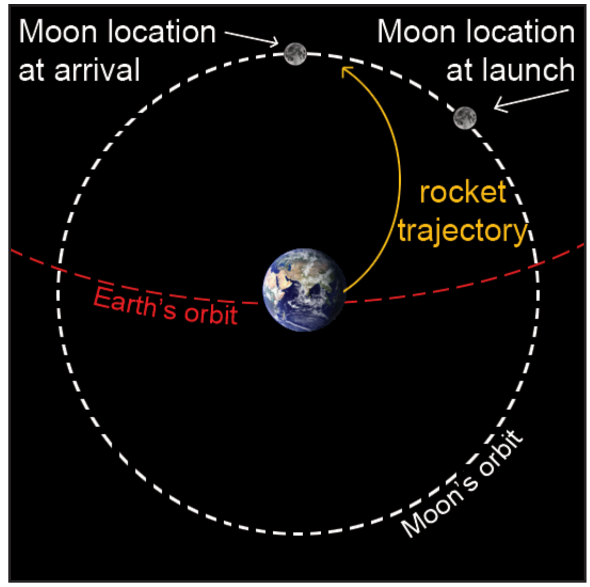
Atlas V Rocket

Starting the Journey

To begin its journey, a spacecraft uses its own onboard rocket engine, or that of an attached rocket booster stage, to fire a long burst that speeds it away from Earth. There is no friction to slow the departing craft, but it is still subject to the pull of gravity, which does reduce its speed. The rocket firing, the duration of which is calculated in advance, provides just enough force to let the craft reach the Moon. (Think of the spacecraft coasting "up" the side of the Earth's gravity well until it falls into the Moon's gravity well.)

Note that the rocket firing is aimed not at the spot where the Moon is at that moment, but where it *will be* when the craft's flight path intersects the Moon's orbit. For example, during the Apollo missions to the Moon, it took about three days for the astronauts to travel from the Earth to the Moon, so the astronauts aimed their craft at the spot in the Moon's orbit where the Moon *would be* about three days later.

If necessary, a Moon-bound spacecraft can adjust its flight path along the way with small corrective rocket firings. These firings are calculated after analyzing the spacecraft's trajectory, using information from tracking stations on Earth. (During Apollo, the astronauts also made star sightings that could be used to refine their flight path, but only as a backup in case they lost radio communications with mission control.)



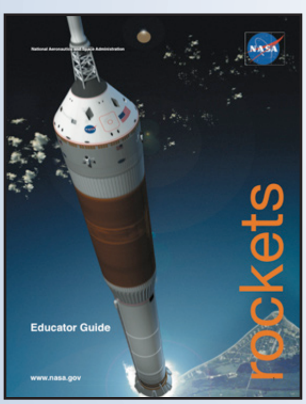
Sample illlustration of aiming for a moving target

"Mystery creates wonder, and wonder is the basis of man's desire to understand."
Neil Armstrong

~ Optional Extension ~

Rockets!

Navigating a spacecraft within the vacuum of space is the primary focus of this challenge; however, planning how to propel a spacecraft through Earth's atmosphere against the force of gravity is critical to the start of any space mission. Visit the following NASA web site to access the free online NASA educational product for rocket information and activities:



"Rockets: Educator's Guide with Activities in Science, Technology, Engineering, and Mathematics" http://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/Rockets.html

The section titled *"How Rockets Work"* (p.19) addresses Newton's laws of motion, and the section *"Applying Newton's Laws"* (p.24) explores rocket engines, propellants, and control systems.

All sections of this guide can be freely downloaded off the web in sections or as a complete guide.

Staying On Course

Radio signals from the Moon-bound spacecraft are received by giant radio antennas of the Deep Space Network (DSN). Aside from the information contained in these signals about the health of the spacecraft, the radio waves themselves provide information on the craft's motion because of a phenomenon called the Doppler shift, which is the apparent change in frequency of sound or light waves emitted by a moving object as seen by a stationary observer. On Earth, we experience the Doppler effect in the whistle of a passing train: The whistle rises in pitch as the train approaches and falls as the train speeds away from us. By measuring the apparent frequency of the moving spacecraft's radio waves, engineers can determine how fast it is moving away from Earth.


70m antenna at Goldstone near Apple Valley, CA

Another important piece of information, the spacecraft's position in the sky, can be determined using two or more antennas located at widely separated DSN stations on Earth (for example, Madrid, Spain and Canberra, Australia) to observe the spacecraft at the same time. At each DSN station, recordings are made of the spacecraft's radio signals. Then, both antennas are turned toward a very distant celestial object called a quasar, whose position on the sky is known with great accuracy. By comparing the radio signals from the spacecraft with the radio waves emitted from the quasar, engineers can make an accurate determination of the spacecraft's position in the sky.

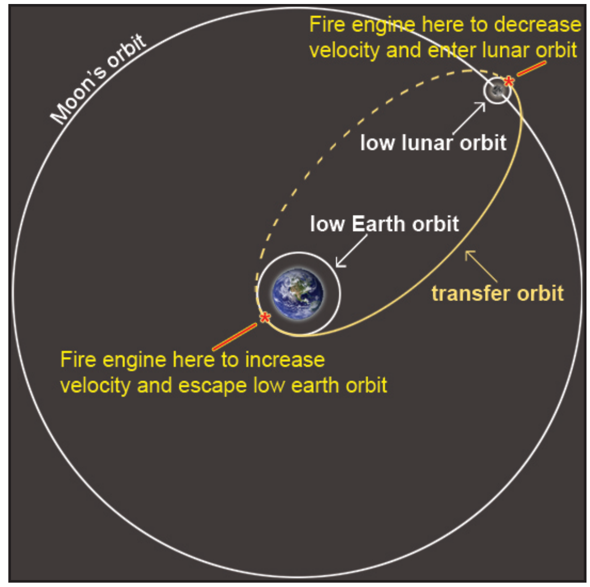
With accurate information on the spacecraft's position and velocity, mission teams can decide whether it is necessary to correct its course, and by how much. They compute the precise duration and direction needed to fire the craft's small onboard thrusters, and they translate this information into a set of commands that are relayed from the DSN to the spacecraft. Aboard the spacecraft, there are instruments to allow the craft to orient itself properly, using the sun and stars, before firing its thrusters.

Orbits

In outer space, objects such as planets, moons, and spacecraft rarely, if ever, travel along straight paths. Instead these objects follow curved, elliptical paths that we call orbits. Whereas planets and moons remained fixed to their orbits, spacecraft often transfer from one orbit to another in order to reach their destination.

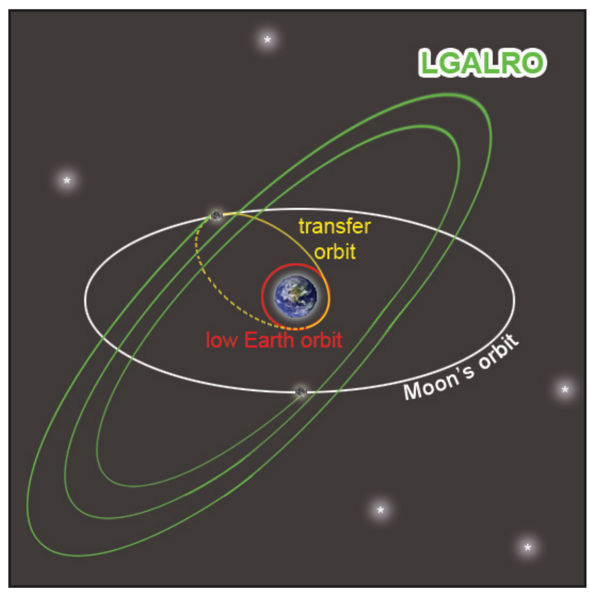
One type of orbit is a “low orbit,” which exists close to the body being orbited. Examples of this are the orbits of the International Space Station and the Space Shuttle, about 200 miles above Earth's surface. Other types of orbits can be much higher; geosynchronous satellites that deliver TV programs into many of your houses orbit at about 22,000 miles above Earth. The Moon has an even higher orbit around Earth at almost 240,000 miles! Higher orbits require higher amounts of energy to enter into. Low orbits require less energy to enter into. Spacecraft typically are placed in a low orbit around the Earth to collect data (as in weather satellites) or a low orbit around the Moon to prepare for a surface landing (as in Apollo spacecraft).

To move between any of these different types of orbits, spacecraft make use of transfer orbits. A “transfer orbit” is an elongated, elliptical orbit whose high and low points are located along the two orbits that the spacecraft is moving to and from. Entering a transfer orbit requires additional energy, usually in the form of a thrust from a spacecraft's rocket engine, which in essence "stretches" the circular low orbital path into the more elliptical transfer orbital path. An example of the use of a transfer orbit is the Apollo 11 mission. The Apollo 11 spacecraft was launched from Earth on a Saturn V rocket, which gave it enough power to enter low Earth orbit. After one and half orbits around Earth, Apollo 11 fired a thrust from its remaining engine that pushed the spacecraft into a transfer orbit directed toward the Moon. Three days later, Apollo 11 approached the Moon, fired its engine once again, and entered a low-energy lunar orbit. As a spacecraft prepares to move from a transfer orbit into a low orbit, it must be slowed down so that the planet or moon's gravitational field can capture it. Not all gravitational fields are the same. Larger celestial bodies (such as Jupiter) have a stronger gravitational pull than smaller celestial bodies (such as our Moon); therefore, the smaller the target, the more the spacecraft must be slowed down in order to be captured.



Sample illlustration of a lunar transfer orbit

Low orbits and transfer orbits are achieved by thrusts from a spacecraft's engine. Rocket propellant is heavy and expensive and a spacecraft is limited on how much fuel it can carry, so sometimes it makes sense to use forces other than that from a spacecraft's engine. One such alternative force is gravity. A "gravity assist orbit" uses the gravitational pull of a celestial body (i.e., planet, moon, or star) to change the course, or trajectory, of a spacecraft by altering the craft's speed and direction. Upon approaching a celestial body, as long as it is traveling faster than the body's escape velocity, a spacecraft can use the body's gravitational field to increase or decrease its momentum and change its course. This technique works well for a spacecraft journeying to distant planets because it reduces the amount of fuel required to conduct orbital maneuvers which, in turn, reduces overall cost. This technique also works for spacecraft needing to significantly change the angle of its trajectory. One example of a gravity assist orbit is a Lunar Gravity Assist Lunar Return Orbit (LGALRO). This orbit, like the transfer orbit, is a high-energy highly elliptical orbit. An LGALRO uses the Moon's gravity to "assist" in escaping a transfer orbit and entering into a larger orbit that encompasses the entire Earth-Moon system. The purpose of an LGALRO is to position a spacecraft along a trajectory that directly intercepts the Moon, hence the term "lunar return orbit." Spacecraft typically are placed in an LGALRO for the purpose of a nearly perpendicular, high-energy impact with the lunar surface. In general, it takes a spacecraft approximately 38 days to complete one LGALRO.



Sample illlustration of a Lunar Gravity Assist Lunar Return Orbit

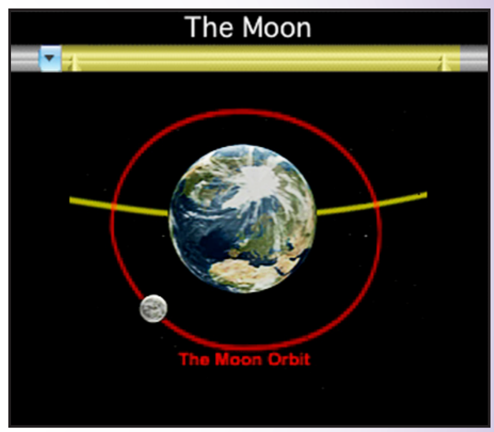
~ Recommended Educational Resource ~

What's the Difference is a free educational tool available for download from the NASA Quest web site: http://quest.nasa.gov/projects/wtd/

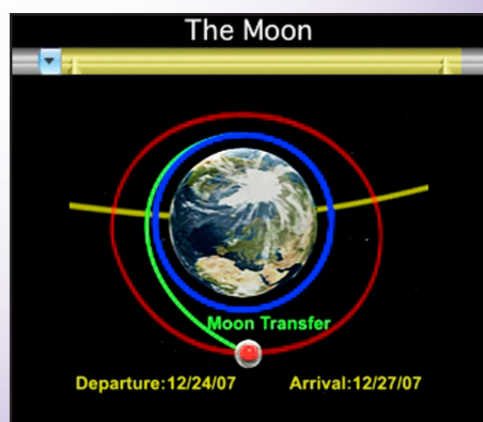
Students can use the **Solar System dataset** housed in ***What's the Difference*** to compare the following key attributes of the Earth and Moon:

- atmosphere
- composition
- cool facts
- diameter
- gravity
- human weight
- planetary data
- transfer orbit
- tilt and rotation
- surface temperature

Students can also select the "surface fly by" and "virtual reality" attributes to dynamically compare the surfaces of the Earth and Moon!



Sample images on the Moon's transfer orbit animation in *What's the Difference*



Download Instructions

Go to: http://quest.nasa.gov/vft/#wtd_download, scroll to the "What's the Difference?" section of the page, locate "Download the Program," and then choose the file for either the Mac or PC. Once downloaded, unzip the file and make sure all contents are saved into a single folder on your computer.

Operating Instructions

Open the folder and double click either "1StartWTDmac" or "1StartWTDpc.exe" (depending on your computer platform). Next, choose the "Solar System" dataset and click the green "Build Application" button. When the black and gray comparison screen appears, select "The Moon" from the drop down menu in one comparison window and select "Earth" from the drop down menu in the other comparison window. Explore and compare the characteristics of the Earth and Moon by clicking on the red attributes listed in the lower half of the application window.

In addition to exploring the different attributes, click the blue "Tools" button on the right border of the application window to access an "orrery" and "planet weight calculator."

Propulsion

Newton's second law of motion explains that an object will change velocity if it is pushed or pulled upon, and Newton's third law of motion states that for every force there is an equal and opposite force. Thrusts from a rocket engine can be used to speed up or slow down a spacecraft. To *increase* a spacecraft's speed, the thrust must be made in the *same* direction in which the spacecraft is traveling. This means that an engine's propellant is ejected in the *opposite* direction, thus pushing (or propelling) the spacecraft forward. To *decrease* speed, the thrust must be made in the *opposite* direction in which the spacecraft is traveling, which means expelling the propellant in the *same* direction of travel, thus slowing the spacecraft down.

~ Recommended Educational Resource ~

Microgravity and Forces and Motion

Give students hands-on experience with forces and motion in a microgravity environment by allowing them to explore the 7 web-based "experiments" on NASA's Personal Satellite Assistant activities page. Each experiment focuses on Newton's laws of motion and addresses a different variable such as mass or movement in one or two dimensions. Once students have completed the mini-experiments, they can test their knowledge with a 4-part web-based "mission" that unites physics and fun.

The online Personal Satellite Assistant activities are available at no cost on the NASA Quest web site: http://psa.arc.nasa.gov/acti.shtml

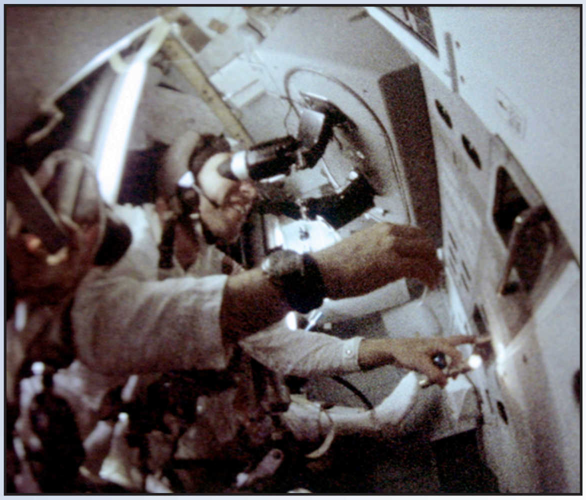
Credits and Sources

The information in this section (pp. 12–19) is attributed to the following sources:

- Chaikin, Andrew. Science Journalist, Space Historian, and Author of "A Man on the Moon: The Voyages of the Apollo Astronauts" http://www.andrewchaikin.com/
- essortment.com. "*The History of Space Travel.*" Retrieved January 2009 from http://www.essortment.com/all/spacetravelhis_rdwh.htm
- NASA.gov. "*Human Space Flight: History.*" Retrieved January 2009 from http://spaceflight.nasa.gov/history/
- Rogers, Dr. Lucy. "It's Only Rocket Science: An Introduction in Plain English" *Chapter 4: Movement in Three Dimensions.* Springer 2008.
- Wikipedia. Information retrieved January 2009 from the following entries:
  - *Apollo Program*. http://en.wikipedia.org/wiki/Apollo_mission
  - *Moon.* http://en.wikipedia.org/wiki/Moon
  - *Spaceflight*. http://en.wikipedia.org/wiki/Space_flight#Human_spaceflight
  - *Space Race*. http://en.wikipedia.org/wiki/Space_race

~ Historical Reflection ~

Navigation on the Apollo Missions



Astronaut Jim Lovell at sextant

The 24 astronauts who flew to the Moon on the Apollo missions were the first human beings to journey away from Earth to another world. During the trip from Earth to the Moon and back, the men rode in a cone-shaped craft called the command module.   The command module was equipped with a sextant for celestial navigation, which was connected to an onboard computer programmed to calculate navigational information. The actual process of navigating aboard Apollo was similar to navigating at sea, in which a sailor uses a sextant to sight on a star and measure its angle relative to the Earth's horizon. In the case of Apollo, however, the entire Earth was visible! So, the astronaut would sight on a specific star, mark the location, and then take a second mark on the edge of the Earth. (Sometimes, the Moon's edge was used instead.) The angle between the two would then be calculated by the onboard computer, which would use the information to update its knowledge of the spacecraft's flight path.

During Apollo missions the primary navigation duties were handled by mission control in Houston, where roomfuls of computers performed the necessary calculations using tracking data from giant radio antennas around the world. The astronauts' onboard navigation was used mostly as a backup, in case the astronauts lost radio contact with Earth during the trip to or from the Moon. Fortunately, that never happened, but the astronauts showed that their own star sightings were accurate enough to have done the job!

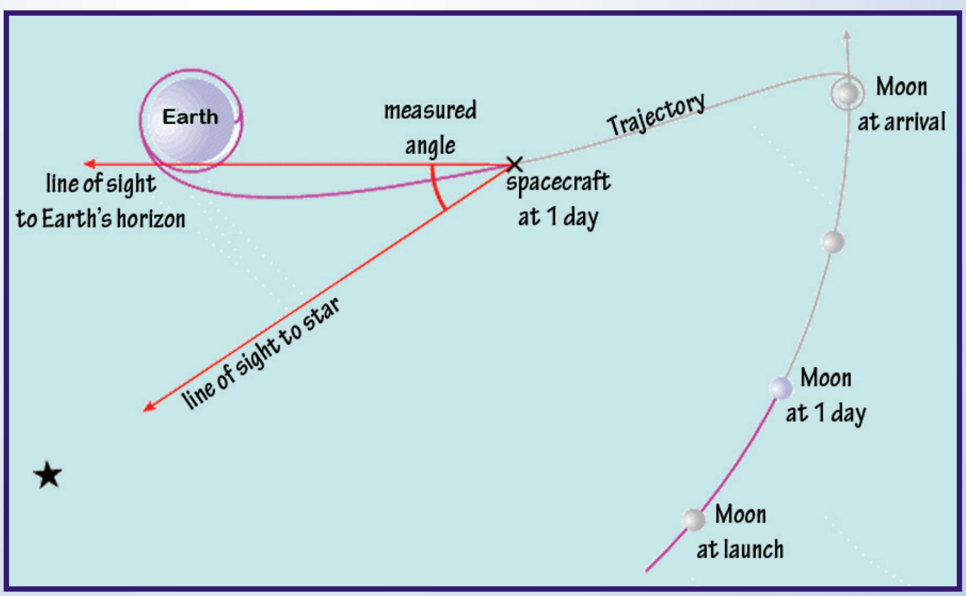


Image Source: NASA History Division. *"The Apollo 8 Flight Journal"*
http://history.nasa.gov/ap08fj/03day1_green_sep.htm

As a class or in teams, explore one or more of the following aspects of space travel:

- Three-dimensional space
- Outer space
- Newton's laws of motion
- Gravity, Escape velocity
- Transfer orbit
- Gravity assist orbit
- Rocket
- Doppler effect
- Radio waves
- Deep Space Network
- Miniature Inertial Measurement Unit
- Spacecraft Propulsion
- Gyroscope
- Attitude dynamics & control
- Star tracker

<u>Three-dimensional space</u>

- Wikipedia. *"Three-dimensional space"* http://en.wikipedia.org/wiki/Three_dimensional_space

<u>Outer space</u>

- NASA Quest. "*Suited for Spacewalking Teacher's Guide: The Outer Space Environment"* http://quest.nasa.gov/space/teachers/suited/3outer.html
- Qualitative Reasoning Group, Northwestern University. Virtual Solar System Project. "*Welcome to the Principles of Operations: What's it like in space?"* http://www.qrg.northwestern.edu/projects/vss/docs/space-environment/subzoom-space.html and *"What is in space?"* http://www.qrg.northwestern.edu/projects/vss/docs/space-environment/zoom-whatis.html
- Wikipedia. *"Outer space"* http://en.wikipedia.org/wiki/Outer_space

<u>Newton's laws of motion</u>

- How Stuff Works. *"Elements of Physics: Newton's Three Laws of Motion"* http://videos.howstuffworks.com/hsw/17164-elements-of-physics-newtons-three-laws-of-motion-video.htm (5 minutes)
- NASA Quest. Personal Satellite Assistant: Key Ideas *"laws of motion"* and *"motion and mass"* video clips http://psa.arc.nasa.gov/keyi.shtml and Activities – online, hands-on *"experiments 1–7"* http://psa.arc.nasa.gov/acti.shtml
- Qualitative Reasoning Group, Northwestern University. Virtual Solar System Project. "*Welcome to the Principles of Operations: "How do objects travel in space?"* http://www.qrg.northwestern.edu/projects/vss/docs/space-environment/zoom-travel.html
- Rice University, Center for Excellence and Equity in Education. Teacher TECH K-12 professional development program. *"Newton's Laws of Motion"* by Georgia Louviere. http://teachertech.rice.edu/Participants/louviere/Newton/index.html
- Wikipedia. *"Newton's laws of motion"* http://en.wikipedia.org/wiki/Newton%27s_laws_of_motion
- Zobel, Ed. Zona Land. Education in Physics and Mathematics. *"Isaac Newton's Laws of Motion"* http://id.mind.net/~zona/mstm/physics/mechanics/forces/newton/newton.html

<u>Gravity</u>

- How Stuff Works. *"Elements of Physics: Gravitation"* http://videos.howstuffworks.com/hsw/10698-elements-of-physics-gravitation-video.htm (2 minutes, 45 seconds)
- How Stuff Works. *"Forces and Gravity: Introduction to Forces and Gravity"* http://videos.howstuffworks.com/hsw/11970-forces-and-gravity-introduction-to-forces-and-gravity-video.htm (3 minutes, 15 seconds)

- How Stuff Works. *"NASA Talks Gravity"* http://videos.howstuffworks.com/nasa/2039-nasa-talks-gravity-video.htm (1 minute)
- Qualitative Reasoning Group, Northwestern University. Virtual Solar System Project. "*Welcome to the Principles of Operations: "What is gravity?"* http://www.qrg.northwestern.edu/projects/vss/docs/space-environment/1-what-is-gravity.html and *"Is there gravity in space?"* http://www.qrg.northwestern.edu/projects/vss/docs/space-environment/1-is-there-gravity-in-space.html and *"What is a gravity well?"* http://www.qrg.northwestern.edu/projects/vss/docs/space-environment/3-whats-a-gravity-well.html
- University of Tennessee, Department of Physics and Astronomy. Astronomy 161 *"The Solar System: The Universal Law of Gravitation"* http://csep10.phys.utk.edu/astr161/lect/history/newtongrav.html
- Wikipedia. *"Gravitation"* http://en.wikipedia.org/wiki/Gravitation
- XPrize Foundation. YouTube *"Earth and Well Gravity Well Comparison"* http://www.youtube.com/watch?v=VBQHtF3WhMw (1 minute, 52 seconds)

Escape velocity

- PhysLink.com. *"What is escape velocity?"* http://www.physlink.com/Education/AskExperts/ae158.cfm
- Qualitative Reasoning Group, Northwestern University. Virtual Solar System Project. "*Welcome to the Principles of Operations: What is escape velocity?"* http://www.qrg.northwestern.edu/projects/vss/docs/space-environment/2-whats-escape-velocity.html
- Wikipedia. *"Escape velocity"* http://en.wikipedia.org/wiki/Escape_velocity

Transfer orbit

- Jet Propulsion Laboratory. *"Basics of Spaceflight:Interplanetary Trajectories"* http://www2.jpl.nasa.gov/basics/bsf4-1.html
- NASA Quest. What's the Difference: Solar System Math, *"Lesson 3: Comparing Planetary Travel Distances"* Teacher Guide pp. 22–24 and Student Workbook pp. 8–14. http://quest.nasa.gov/vft/#wtd
- Wikipedia. *"Hohmann transfer orbit"* http://en.wikipedia.org/wiki/Transfer_orbit

Gravity assist

- Jet Propulsion Laboratory. *"Basics of Spaceflight:Interplanetary Trajectories"* http://www2.jpl.nasa.gov/basics/bsf4-1.html
- JLR Group, Inc. YouTube. *"Voyager 1 and 2 Trajectories to the Outer Planets"* http://www.youtube.com/watch?v=cTIGOe5ckj0 (1 minute, 18 seconds)
- Northrop Grumman. *"LCROSS mission overview"* http://www.st.northropgrumman.com/media/presskits/mediaGallery/LCROSS/videos/media2_1_24476_25754.html (7 minutes, 30 seconds)
- Wikipedia. *"Gravity assist"* http://en.wikipedia.org/wiki/Gravity_assist
- YouTube. *"Messenger Probe Launch to Orbit Trajectory"* http://www.youtube.com/watch?v=Ownzbb1mKxs (42 seconds)
- YouTube. *"STEREO Getting Into Position"* http://www.youtube.com/watch?v=bhZ-yZwUBpQ (13 seconds)

Rocket

- How Stuff Works. *"How Rocket Engines Work"* http://www.howstuffworks.com/rocket.htm

- How Stuff Works. *"The Rockets: The Saturn V Rocket"* http://videos.howstuffworks.com/hsw/8431-the-rockets-the-saturn-v-rocket-video.htm (3 minutes, 30 seconds)
- NASA.gov. "*Rockets: Educator's Guide with Activities in Science, Technology, Engineering, and Mathematics"* http://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/Rockets.html
- Qualitative Reasoning Group, Northwestern University. Virtual Solar System Project. "*Welcome to the Principles of Operations: How do conventional rockets work?"* http://www.qrg.northwestern.edu/projects/vss/docs/Propulsion/zoom-conventional.html and *"How are rockets designed?"* http://www.qrg.northwestern.edu/projects/vss/docs/Propulsion/1-how-are-rockets-designed.html
- Wikipedia. *"Rocket"* http://en.wikipedia.org/wiki/Rocket

Doppler effect

- Fendt, Walter. *"An Example of Doppler Effect"* http://www.walter-fendt.de/ph11e/dopplereff.htm
- University of Virginia, Physics Department. Professor Michael Fowler. Physics 109: Galileo and Einstein. Flashlet: "*Doppler Effect"* http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/doppler.htm
- Wikipedia. *"Doppler effect"* http://en.wikipedia.org/wiki/Doppler_effect

Radio waves

- How Stuff Works. *"How Radio Works"* http://www.howstuffworks.com/radio.htm
- NASA Science. NASA Science for Kids. *"The Electromagnetic Spectrum: Radio Waves"* http://science.hq.nasa.gov/kids/imagers/ems/radio.html
- Wikipedia. *"Radio waves"* http://en.wikipedia.org/wiki/Radio_waves

Deep Space Network

- Jet Propulsion Laboratory. *"Basics of Spaceflight: Deep Space Network"* http://www2.jpl.nasa.gov/basics/bsf18-1.html
- Jet Propulsion Laboratory. *"Deep Space Network"* http://deepspace.jpl.nasa.gov/dsn/
- Qualitative Reasoning Group, Northwestern University. Virtual Solar System Project. "*Welcome to the Principles of Operations: How do we know a spacecraft's location?"* http://www.qrg.northwestern.edu/projects/vss/docs/Navigation/1-how-do-we-know-location.html
- Wikipedia. *"Deep Space Network"* http://en.wikipedia.org/wiki/Deep_space_network

Miniature Inertial Measurement Unit

- Wikipedia. *"Miniature Inertial Measurement Unit"* http://en.wikipedia.org/wiki/Miniature_Inertial_Measurement_Unit_(MIMU)

Spacecraft propulsion

- Qualitative Reasoning Group, Northwestern University. Virtual Solar System Project. "*Welcome to the Principles of Operations: How do spacecraft propel themselves through space?"* http://www.qrg.northwestern.edu/projects/vss/docs/Propulsion/subzoom-propulsion.html
- Wikipedia. *"Spacecraft propulsion"* http://en.wikipedia.org/wiki/Spacecraft_propulsion

Gyroscope

- How Stuff Works. *"How Gyroscopes Work"* http://www.howstuffworks.com/gyroscope.htm
- Wikipedia. *"Gyroscope"* http://en.wikipedia.org/wiki/Gyroscope

Attitude dynamics and control

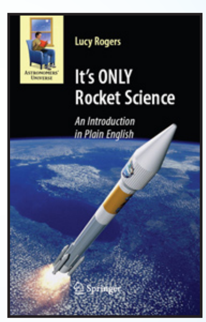
- Air Force Air War College. Basics of Space Flight Learner's Workbook. *"Chapter 13: Spacecraft Navigation"* http://www.au.af.mil/au/awc/awcgate/jplbasic/bsf13-1.htm
- Answers.com. *"Space Navigation and Guidance"* http://www.answers.com/topic/space-navigation-and-guidance
- Deep Space Navigation Concept Map. http://cmapsnasacmex.ihmc.us/servlet/SBReadResourceServlet?rid=1025201019947_694487307_2109&partName=htmltext
- Jet Propulsion Laboratory. *"Basics of Spaceflight"* http://www2.jpl.nasa.gov/basics/
- Qualitative Reasoning Group, Northwestern University. Virtual Solar System Project. "*Welcome to the Principles of Operations."* http://www.qrg.northwestern.edu/projects/vss/docs/index.html and *"How do DS1 and other spacecraft navigate?"* http://www.qrg.northwestern.edu/projects/vss/docs/Navigation/subzoom-nav.html and *"How do scientists know what the path of an object in space will be?"* http://www.qrg.northwestern.edu/projects/vss/docs/space-environment/1-how-do-scientists-know-path.html
- Wikipedia. *"Attitude dynamics and control"* http://en.wikipedia.org/wiki/Attitude_dynamics_and_control

Star tracker

- NASA.gov. Lunar Reconnaissance Orbiter Mission. *"Star Trackers Light the Way"* http://www.nasa.gov/mission_pages/LRO/main/index.html (video located in the far right panel of the web page: 2 minutes, 40 seconds)
- NASA Kennedy Space Center. Science, Technology, and Engineering. *"Space Shuttle Information Reference Manual: Space Shuttle Orbiter Systems: Communications: Avionics Systems: Guidance, Navigation, and Control: Star Trackers"* http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-gnnc.html#sts-star-tracker

Additional Resources

"A Man On the Moon: The Voyages of the Apollo Astronauts"
by Andrew Chaikin



"It's Only Rocket Science: An Introduction in Plain English"
by Dr. Lucy Rogers

~ Note to Teacher ~

The topics explored in the "What" section of this guide (pp.12–24) do not encompass all aspects or methods of space navigation. There is no single "right answer" to this challenge, so as students begin devising a navigation plan in the "How" section (pp.25–28), they are invited to think outside the box and suggest alternative, innovative space navigation strategies in addition to those addressed in this guide.

Ho'ohana (How)

Driving Question

Challenge:
Devise a plan to navigate an unmanned spacecraft from Kennedy Space Center at Cape Canaveral, Florida, to a permanently shadowed crater at the Moon's north pole. As part of this task, you will need to:

- Work as a team.
- Plan a route from your starting point (Earth) to your destination (Moon).
- Be able to determine your spacecraft's location in outer space (establish a frame of reference) once it has departed Earth.
- Locate and impact your destination (the Moon's north pole).

Constraints:

- Your spacecraft will <u>not</u> be able to use traditional Earth-based navigational tools such as a Global Positioning Satellite (GPS) or magnetic compass.
- Your spacecraft will <u>not</u> be able to travel in a straight line.
- Your spacecraft will be unmanned.

Deliverable:
In order to accommodate all participating classes, each class should submit ***<u>one</u>*** navigation plan to NASA Quest. Although students may work in teams and develop more than one solution to this challenge, the class should choose the best navigation plan to submit. This submission should include:

- Explanatory text describing the planned voyage and means of navigation (template on p. 27)
- Visual representation of your method(s) of navigation (Be creative! Suggestions include: collage of tools, drawing of vessel or instruments, flow chart or concept map, etc.)
- Map of planned space route (template of Earth and Moon on p. 28 and sample map on p. 29)

Submit to NASA Quest via email or regular mail:

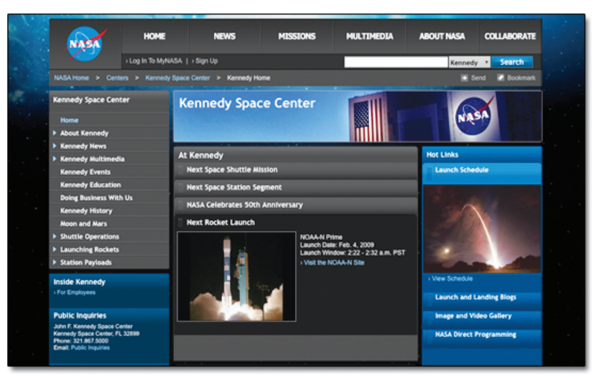
Email: Linda.B.Conrad@nasa.gov

Mail: Quest Space Navigation Challenge
c/o Linda Conrad
NASA Ames Research Center
Mailstop 226-4
Moffett Field, CA 94035

Considerations:
Students should consider the following while planning their voyage:

- On average, the Moon is 384,400 km from Earth.
- A spacecraft can reach the Moon in as quickly as 2–4 days; however, this time frame will not allow for proper alignment with the Moon's north pole.
- The location of the Moon in reference to Earth will change between the time of launch and the time of impact.
- Celestial objects, such as stars, can be used as a frame of reference.
- Seasonal weather conditions, such as thunderstorms, around Cape Canaveral can pose a serious threat to the successful launch of rockets and spacecraft.
- The Lunar Reconnaissance Orbiter (LRO) is the sister spacecraft launching with LCROSS, and its purpose is to map the surface of the Moon. In the early stages of its mission, LRO can gather and send useful information to you and your science team that will help you select an impact site. Consider the amount of time needed for LRO to gather and send relevant data to you and your team as well as the time you and your team will need to select an impact site and relay that information to the LCROSS spacecraft.

- What route will it follow? Will it use a transfer orbit or an LGALRO?
- How many days, weeks, or months will the journey take?
- How will you navigate and control your craft?
- How will you know your spacecraft's location along its journey?
- How will you guide your craft so that it impacts the Moon's north pole at a steep angle between 65º–70º?



Learn more about KSC at:
http://www.nasa.gov/centers/kennedy/home/

Navigation Plan: Earth to Moon

Team name:

Spacecraft name:

Launch time and date:

Duration of journey:

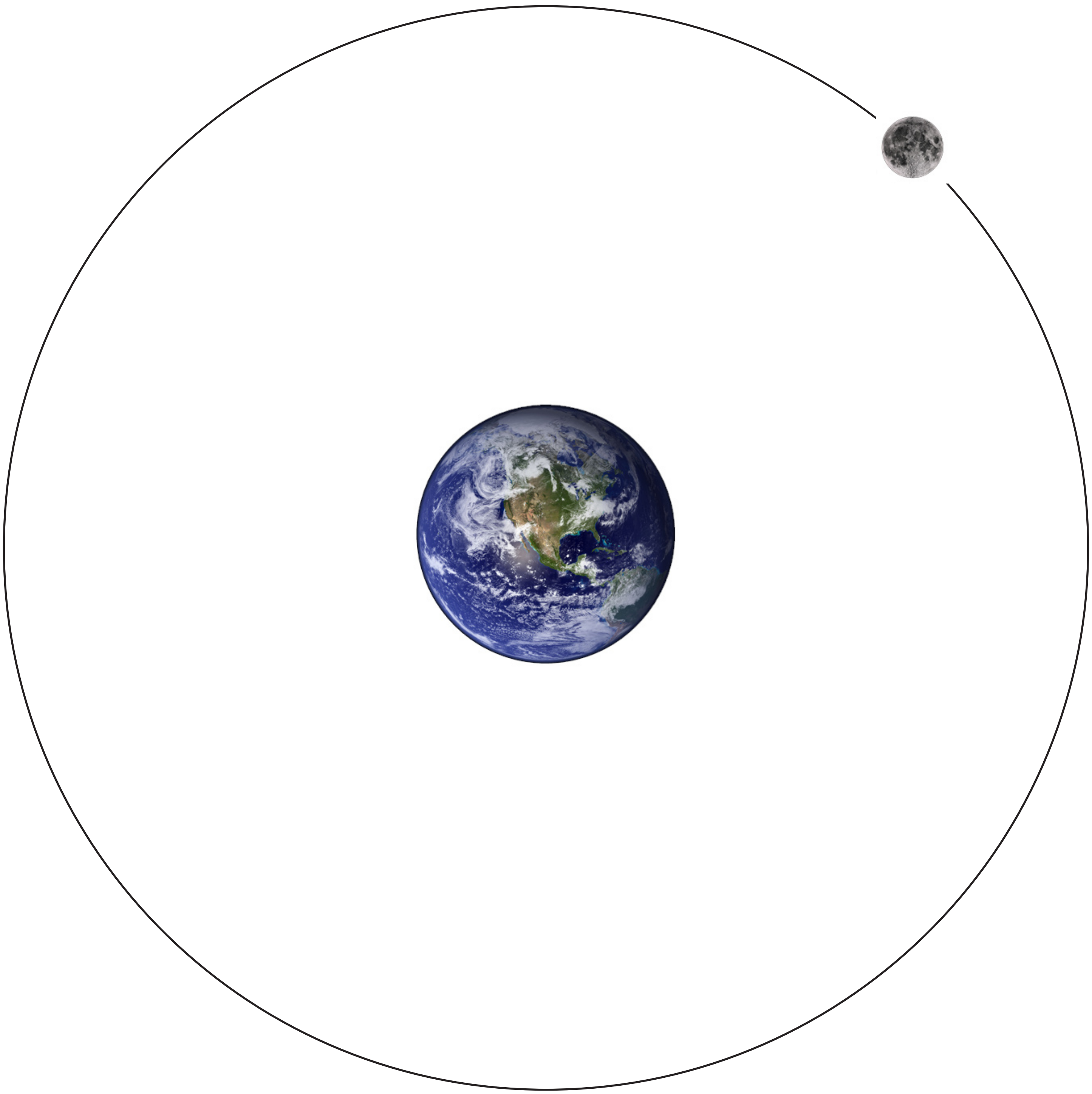
Expected impact date:

Description of route and orbital paths:

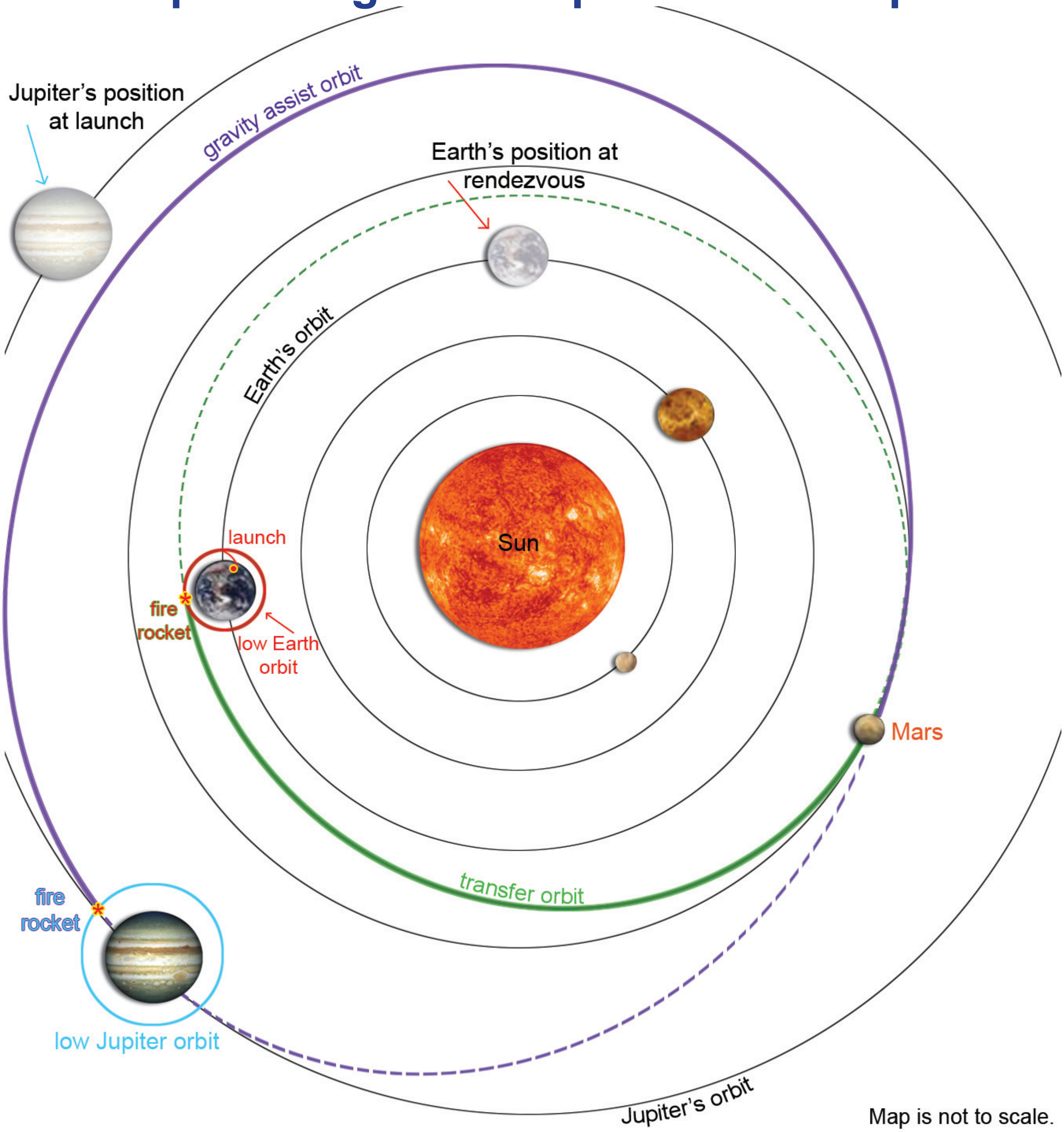
Navigation Instruments:

Methods of guidance, navigation, control, and tracking:

Navigation Map: Earth to Moon



Sample Navigation Map: Earth to Jupiter



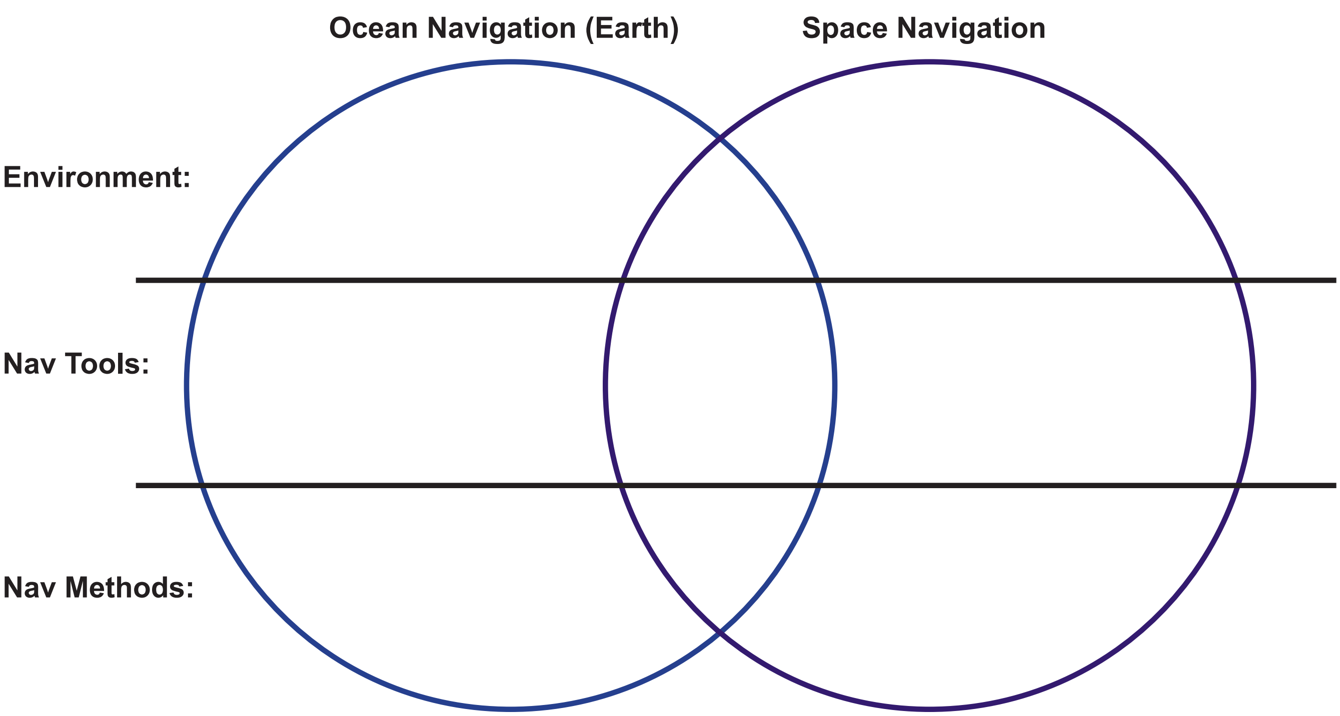
Map is not to scale.

Ho'opuka (If)

Driving Question:

Discuss with students the possibilities of how they can use and extend their new-found knowledge about space navigation.

- If you can successfully navigate to the Moon, then what destination might you choose to explore beyond our Moon? How would you get there?
- If you were to create a new navigation method, what would it be?
- LCROSS is a "robotic" lunar mission. Do you think it is best for robots, for humans, or for a combination of both to explore outer space? Why?
- If LCROSS finds water ice on the Moon's surface, then what do you think should be the next step of space exploration?
- If humans built a colony on the Moon, what resources other than water would they need to survive, to work, and to have a satisfactory quality of life?
- How is navigating the seas on planet Earth different than navigating in three-dimensional space? Compare and contrast the environments, tools, and navigation methods used in regard to sea and space exploration.



Problem Situation! (for students)

The Problem

Off Course!

You are the navigation officer on the LCROSS mission control team. You have just received new tracking data that says the spacecraft is off course and will miss its impact point by 10 kilometers! That is to say, the spacecraft will fall 10 kilometers short of the target crater.

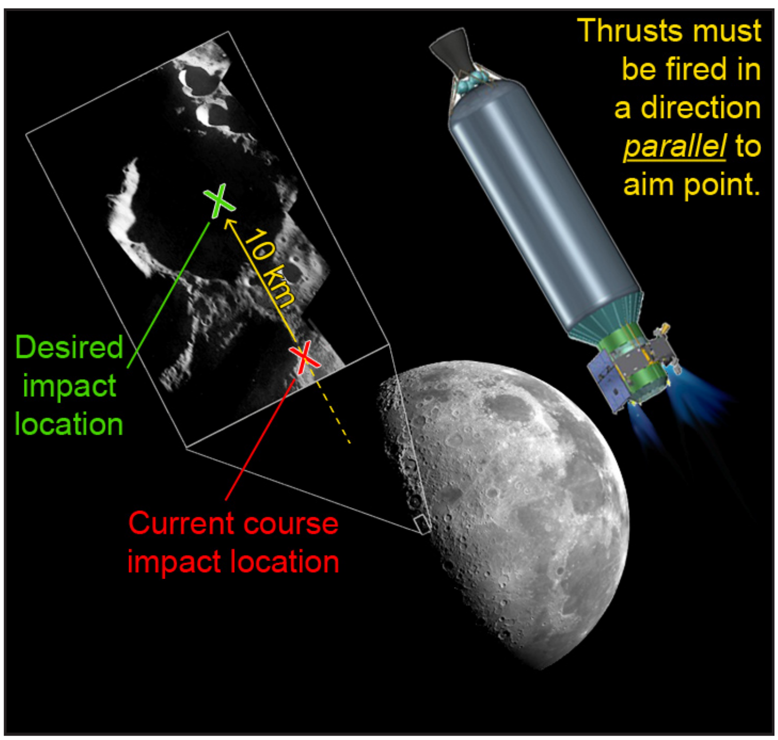
The spacecraft is currently 10 hours from impact on the Moon, and there is a final opportunity to perform a correction maneuver 2 hours from now. If the spacecraft weighs 7,275 pounds, then:

How long must you fire the onboard thrusters to get back on target and save the mission?

Key Concept

As the great English scientist Isaac Newton first stated, moving objects have a property that causes them to continue moving unless acted on by a force. The same property causes an object at rest to remain at rest if no force acts upon it. Newton called this property **inertia**.

On Earth, one of the forces acting on a moving object to slow it down is **friction**. Airplanes experience friction with the air; sailing ships encounter friction from the water; cars are slowed by friction with the road. Yet in the vacuum of space there is no friction. It's as if everything were moving on a perfectly smooth, 3-dimensional ice rink. So, if you fire a spacecraft's thruster, even for just a brief moment, it will cause an increase or decrease in the spacecraft's velocity that will remain in effect indefinitely until the spacecraft is acted upon by another force. Therefore, one way to counteract a burst from a thruster in one direction is to fire a burst in the *opposite* direction.



Important Information

LCROSS has 2 onboard thrusters for trajectory correction maneuvers, each of which produces 5 pounds of thrust. Both thrusters always fire together. To change LCROSS's aim point on the Moon, you must fire its thrusters in a direction *parallel* to the direction you wish to shift the aim point. (See illustration above.)

Problem Solution (for teachers)

Approaching the Problem

The *Problem Situation* on page 31 is for you to present to your students. The *Problem Solution* on pages 32–39 is for you, the teacher, to review to help you understand the science and math used to solve this problem.

The physics concepts associated with this problem are advanced and are more suitable for upper grade levels; however, the mathematics are centered mostly on unit conversion and multiplying and dividing fractions, which is fitting for lower grade levels. You, the teacher, can decide how much or how little the students need to know in order to solve this problem. For example, teachers of upper level students may wish to explore the physics and units of measurement in depth and to work through the solution step by step, whereas teachers of lower level students may choose to give students the numerical values to plug into the equations, making this simply a math problem.

Don't be intimidated by the solution to this problem. It is based on two equations: force equals mass times acceleration (F = m a) and velocity equals acceleration times time (v = a t). We will begin by reviewing each of the physics concepts associated with these two equations. Next, we will rewrite these equations, as needed, and solve for each variable one by one. Then, as the final step, we will derive the amount of *time* (t) that the thrusters need to be fired by dividing velocity (v) by acceleration (a).

In this guide, the solution is worked using both the International System of units (also known as the metric system or SI) and the Customary System of units (also known as English or Standard units). For each equation, you will see the solution worked for both systems side by side. You should choose the one system that is most appropriate for your students; it is not necessary for your students solve the problem for both systems of measurement.

Situation Summary

Ten hours remain before impact, and the spacecraft is currently on a course that will miss the target crater by 10 kilometers. Two hours from now, that is to say at 8 hours from impact, the rocket thrusters will need to be fired so that the spacecraft's course is changed by 10km over a period of 8 hours. The total combined *weight* of the Centaur upper stage and the LCROSS shepherding spacecraft is 7,275 pounds. The spacecraft has two rocket thrusters, and each rocket delivers 5 pounds of thrust for a combined total thrust of 10 pounds of force. This can be summarized as follows:

Required correction:	10 km
Time for correction:	8 hr
Velocity change (delta-V):	10 km / 8 hr
Total spacecraft weight:	7,275 lb
Total rocket thrust:	10 lbs of force

Main Idea

In spaceflight, it is common to make mid-flight course corrections by firing onboard thrusters to change a spacecraft's velocity. The amount of time that the thrusters need to be fired to properly correct the course can be determined using the simple equation:

time = velocity ÷ acceleration

Forces and Motion

There are many factors to consider when solving this problem, including force, mass, weight, acceleration, velocity, and time.

A **force** (F) is anything, such as a push or a pull, that changes an object's velocity or causes an object to move. Force has both a magnitude and a direction. Newton's second law can be stated as "force equals mass times acceleration," meaning the net force on an object is equal to the mass of the object multiplied by its acceleration.

$$F = m\ a$$

Remember, in the frictionless environment of outer space, objects will continue to move along a new path and at a new velocity when acted upon by a force until they are acted upon by another force, in this case the impact.

Mass (m) is a measure of the quantity of matter an object contains. Mass is not a force and is not the same thing as weight. Whether an object is on the surface of the Earth, on the surface of the Moon, or free falling through space, its mass will remain the same (unless, of course, the object itself is changed by adding to or taking away from its mass). In the International System of units (SI), mass is measured in *kilograms* (kg), and in the Customary System of units, mass is measured in *slugs*.

Weight is the force of gravity acting on an object. Since weight (w) is a force and the acceleration of the object being weighed is due to gravity (g), we can rewrite Newton's "F = m a" equation in a special form:

$$w = m\ g$$

Weight is a force and should not be confused with mass. Since the weight of an object is determined by both the object's mass *and* the force of gravity pulling on the object, the object's weight will vary whether it is on the surface of the Earth, on the surface of the Moon, or free falling through space because the force of gravity is different for each of these locations. The standard units of weight are the *newton* (N) for SI and the *pound* (lb) for Customary.

Fun Fact!

Because an object's *mass* does not change, the amount of force needed to move the object does not change either. For example, the same amount of force is required to bowl a bowling ball on the Moon as is required to bowl a bowling ball on Earth.

The *weight* of the bowling ball is less on the Moon than it is on Earth, but the *mass* of the bowling ball is the same in both locations. Therefore the same amount of effort (or force) is needed to move the bowling ball in both locations.

Kilograms vs. Newtons	**Slugs vs. Pounds**
The kilogram (kg) is a unit of mass, and the newton (N) is a unit of weight (force). One newton of force will accelerate a mass of 1 kilogram at a rate of 1 meter per second per second.	*The slug is a unit of mass, and the pound (lb) is a unit of weight (force). One pound of force will accelerate a mass of 1 slug at a rate of 1 foot per second per second.*
$1\ \text{N} = (1\ \text{kg})\ \left(\frac{1\ \text{m}}{\text{s}^2}\right)$	$1\ \text{lb} = (1\ \text{slug})\ \left(\frac{1\ \text{ft}}{\text{s}^2}\right)$
We can also say that, on Earth, the weight of 1 kilogram is 9.8 newtons. (See table below.)	*We can also say that, on Earth, the weight of 1 slug is 32.2 pounds. (See table below.)*

Velocity is defined as the rate of change of position. It is a vector and can change in two ways: a change in magnitude and/or a change in direction. Velocity is defined by both speed (magnitude) and direction and is measured in meters per second (m/s) in SI units and in feet per second (ft/s) in Customary units. Velocity (v) equals acceleration (a) times time (t) as shown by the following formula:

$$v = a\ t$$

Acceleration is the change in velocity over time. Acceleration is measured in meters per second per second (m/s^2) in SI units and in feet per second per second (ft/s^2) in Customary units.

Fun Fact!

Ignoring air resistance, any and all objects regardless of their weights, when dropped from the same height, will hit the ground at the same time.

You can find images and video of this experiment being conducted on the Moon at:

http://nssdc.gsfc.nasa.gov/planetary/lunar/apollo_15_feather_drop.html

On average, the strength of **gravity** at the Earth's surface (g) is 9.80665 meters per second per second or 32.174049 feet per second per second. These values can be rounded to 9.8 m/s^2 and 32.2 ft/s^2 respectively.

SI	Customary
$g \approx 9.8$ m/s^2	$g \approx 32.2$ ft/s^2

This means that, ignoring air resistance, an object falling freely near the Earth's surface increases its velocity by 9.8 m/s (32.2 ft/s) for each second of its descent. Thus, an object starting from rest will attain a velocity of 9.8 m/s (32.2 ft/s) after one second, 19.6 m/s (64.4 ft/s) after two seconds, and so on, adding 9.8 m/s (32.2 ft/s) for each succeeding second.

The **g-force** of an object is its acceleration relative to free fall. **Free fall** is motion with no acceleration other than that provided by gravity. An acceleration of 1 g is generally considered as equal to standard gravity, which on Earth is generally defined as 9.8 m/s^2 (32.2 ft/s^2).

Solving the Problem

This problem can be solved using International units (SI) or Customary units. The important thing to remember is to make sure that the correct units are used for the force and velocity equations, and to convert to appropriate units of measurement when necessary. The two formulas we will use to solve this problem are:

Force equals mass times acceleration $F = m\ a$

Velocity equals acceleration times time $v = a\ t$

Let's begin with the force equation. In the equation $F = m\ a$, "force" (F) must be in newtons (N) for SI or in pounds (lb) for Customary and "mass" (m) must be in kilograms (kg) for SI or in slugs for Customary.

In this problem situation, we know that the two onboard rockets will create a combined total of 10 pounds of thrust. This means that the ***force*** of the rocket egines is equal to 10 pounds, or ~ 44.5 newtons.

SI	Customary
Pounds can be converted to newtons using the unit ratio: $\frac{1\text{ N}}{0.2248089\text{ lb}}$ $F = 10\ \cancel{\text{lb}} \cdot \frac{1\text{ N}}{0.2248089\ \cancel{\text{lb}}}$ $F = 44.4822\text{ N}$ $\mathbf{F \approx 44.5\ N}$	$\mathbf{F = 10\ lb}$

We also know that the combined total ***weight*** of the LCROSS and Centaur upper stage is 7,275 pounds.

SI	Customary
Pounds can be converted to newtons using the unit ratio: $\frac{1\text{ N}}{0.2248089\text{ lb}}$ $w = 7{,}275\ \cancel{\text{lb}} \cdot \frac{1\text{ N}}{0.2248089\ \cancel{\text{lb}}}$ $w = 32{,}360.8185\text{ N}$ $\mathbf{w \approx 32{,}360.8\ N}$	$\mathbf{w = 7{,}275\ lb}$

As mentioned on page 33, when working with weight, the force equation can be rewritten as:

$$w = m\ g$$

Since we know the value for weight (w) and the value for gravity (g), we can rewrite this equation to find the ***mass*** (m) of the spacecraft as follows:

$$m = \frac{w}{g}$$

When solving for mass, our units will need to be in kilograms (kg) for SI or slugs for Customary. Let's take another look at the relationship between mass and weight for both systems of units.

SI: Relationship between weight in newtons and mass in kilograms

$$F = m\ a$$

$$F\ (\text{newton}) = m\ (\text{kilogram}) \bullet a\ (\text{meters/second/second})$$

Special case (for acceleration due to gravity only):

$$w = m\ g$$

$$w\ (\text{newton}) = m\ (\text{kilogram}) \bullet g\ (\text{meters/second/second})$$

On Earth: $$w\ (\text{newton}) = m\ (\text{kilogram}) \bullet 9.8\ \text{meters/second/second}$$

To solve for mass: $$m = \frac{w}{g}$$

$$m\ (\text{kilogram}) = \frac{w\ (\text{newton})}{9.8\ \text{meters/second/second})}$$

The corresponding mass (m) in kilograms of a weight (w) in newtons is determined by dividing the weight (w) by gravity (g), which on Earth is 9.8 meters/second/second.

Customary: Relationship between weight in pounds and mass in slugs

$$F = m\ a$$

$$F\ (\text{pound}) = m\ (\text{slug}) \cdot a\ (\text{feet/second/second})$$

Special case (for acceleration due to gravity only):

$$w = m\ g$$

$$w\ (\text{pound}) = m\ (\text{slug}) \cdot g\ (\text{feet/second/second})$$

On Earth: $$w\ (\text{pound}) = m\ (\text{slug}) \cdot 32.2\ \text{feet/second/second}$$

To solve for mass: $$m = \frac{w}{g}$$

$$m\ (\text{slug}) = \frac{w\ (\text{pound})}{32.2\ \text{feet/second/second}}$$

The corresponding mass (m) in slugs of a weight (w) in pounds is determined by dividing the weight (w) by gravity (g), which on Earth is 32.2 feet/second/second.

Now we are ready to solve for the ***mass*** (m) of the spacecraft:

$$m = \frac{w}{g}$$

SI	Customary
$m = \frac{32{,}360.8\ \text{N}}{9.80665\ \text{m/s}^2}$	$m = \frac{7{,}275\ \text{lb}}{32.2\ \text{ft/s}^2}$
$m = \frac{32{,}360.8\ \text{kg}\ (\cancel{\text{m/s}^2})}{9.80665\ \cancel{\text{m/s}^2}}$	$m = \frac{225.93\ \text{lb}}{\text{ft/s}^2}$
$m = 3{,}299.88\ \text{kg}$	$m \approx \frac{226\ \text{lb}}{\text{ft/s}^2}$
	or
$m \approx 3{,}300\ \text{kg}$	**$m \approx 226\ \text{slugs}$**

We can solve for ***acceleration*** (resulting from firing the thrusters) by rewriting the equation again so that force is divided by mass.

$$a = \frac{F}{m}$$

SI	Customary
$a = \dfrac{44.5\ N}{3{,}300\ kg}$	$a = \dfrac{10\ lb}{226\ slugs}$
$a = \dfrac{44.5\ \cancel{kg}\ (m/s^2)}{3{,}300\ \cancel{kg}}$	$a = \dfrac{10\ \cancel{lb}}{} \cdot \dfrac{ft/s^2}{226\ \cancel{lb}}$
$a = 0.01348\ m/s^2$	$a = 0.04425\ ft/s^2$
$\mathbf{a \approx 0.0135\ m/s^2}$	$\mathbf{a \approx 0.044\ ft/s^2}$

For this situation, the spacecraft needs to change (in this case, *increase*) ***velocity*** such that it will travel 10 additional kilometers over an 8 hour period. We can write this change in velocity (delta-V) as:

$$\text{delta-V} = \frac{10\ km}{8\ hr}$$

To make future calculations more manageable, we can write delta-V as a decimal.

$$\text{delta-V} = \frac{10\ km}{8\ hr}$$

$$\text{delta-V} = 1.25\ km/hr$$

Next, we can convert the units of from kilometers per hour (km/hr) to meters per second (m/sec) for SI and to feet per second (ft/s) for Customary.

SI	Customary
First, convert kilometers to meters using the unit ratio: $\dfrac{1{,}000\ meters}{1\ kilometer}$	First, convert kilometers to feet using the unit ratio: $\dfrac{3{,}280.8399\ feet}{1\ kilometer}$
$\text{delta-V} = \dfrac{1.25\ \cancel{km}}{1\ hr} \cdot \dfrac{1{,}000\ m}{1\ \cancel{km}}$	$\text{delta-V} = \dfrac{1.25\ \cancel{km}}{1\ hr} \cdot \dfrac{3{,}280.8399\ ft}{1\ \cancel{km}}$
$= 1{,}250\ m/hr$	$= 4{,}101.04988\ ft/hr$

SI	Customary
Then, convert hours to seconds using the unit ratio: $\frac{1 \text{ hour}}{3{,}600 \text{ seconds}}$	Then, convert hours to seconds using the unit ratio: $\frac{1 \text{ hour}}{3{,}600 \text{ seconds}}$
$\text{delta-V} = \frac{1{,}250 \text{ m}}{1 \cancel{\text{hr}}} \bullet \frac{1 \cancel{\text{hr}}}{3{,}600 \text{ s}}$	$\text{delta-V} = \frac{4{,}101.04988 \text{ ft}}{1 \cancel{\text{hr}}} \bullet \frac{1 \cancel{\text{hr}}}{3{,}600 \text{ s}}$
delta-V = 0.3472 m/s	delta-V = 1.1392 ft/s
delta-V ≈ 0.35 m/s	**delta-V ≈ 1.14 ft/s**

In this problem situation, velocity can be thought of as acceleration times time. This is written as:

$$v = a\ t$$

Now that we know the change in velocity (v) and the rate of acceleration (a), we can solve for ***time*** (t) by rewriting the equation " v = a t " as:

$$t = \frac{v}{a}$$

SI	Customary
$t = \frac{0.35 \cancel{\text{m/s}}}{0.0135 \cancel{\text{m/s}}^2}$	$t = \frac{1.14 \cancel{\text{ft/s}}}{0.044 \cancel{\text{ft/s}}^2}$
t = 25.9259 s	t = 25.90909 s
t ≈ 25.9 seconds	**t ≈ 25.9 seconds**

Solution

The thrusters will need to be fired for 25.9 seconds in order to change the course of the spacecraft by 10 kilometers over an 8 hour period.

Note: Answers will vary based on approximation and rounding.

Credits and Sources

The information in the Problem Situation and Solution section (pp. 31–39) is attributed to the following sources:

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